Soil Dynamics and the Earthquake Destruction of the Earthen Architecture of the Arg-e Bam

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ABSTRACT: *The Arg-e Bam is a remarkable example of earthen architecture and construction that was heavily damaged in the Bam, Iran earthquake of 26 December 2003. This paper presents the hypothesis that the collapse of the walls was caused largely by a combination of the effects of (1) the additive changes made to the walls, particularly in recent restorations resulting in variations in the density and response to vibrations of different layers of unfired earth construction in the walls, and (2) extensive damage from termites and loss of the cohesion of the clay from degradation and excessive drying out, all of which interacted with the earthquake vibrations of unusually high frequency in such a way that many walls effectively burst from the subsidence of their clay internal cores. Concern is raised about the possibility of similar risks to other earthen monumental structures from future earthquakes.*

Keywords: Earthen architecture; Earthen construction; Adobe, Khesht; Cob; Chineh; Termites; Soil dynamics; Earthquake vibration frequency; Vertical earthquake accelerations; Bam citadel; Arg-e Bam; Bam earthquake; Iran

1. Introduction

During the four months that followed the December 26, 2003 earthquake that destroyed much of the Iranian desert city of Bam, much has been said in the international press about the damage to the Arg-e Bam, a majestic historic earthen walled citadel in Iran, see Figure (1). Nowhere in this coverage, however, were there any comments about termites. While I was on a visit to the ruins of the Arg during the International Workshop on Bam sponsored by *UNESCO*, *ICOMOS*, and the Iranian Cultural Heritage Organization (*ICHO*) and, I noticed evidence of an insect infestation in the broken remains of the city's walls. The Iranian archeologists working on the site identified the insects as termites, explaining to me that such termites are relatively common in Iran, but few other conservation architects or engineers with whom I spoke were aware of the termites in the Arg [1].

While there is no question but that termites did not cause the destruction of the historic Arg-e Bam, the evidence of extensive infestation in the ancient earthen monument was unmistakable, see Figure (2). This raises the following question: Did this infestation contribute to the extraordinarily large amount of earthquake damage? While it took only 12 seconds for the earthquake to shake this majestic monument down into formless piles of rubble, the seeds of its destruction in this earthquake may have been laid over the many centuries of continuous erosion, decay, and rebuilding that have taken place on the site. When assessing earthquake damage to an earthen site, it is often easy to look no further than the earthquake shaking itself before considering any peculiarities, such as insects, that may have further weakened the earthen walls.

Many engineers and seismologists have pointed to the intensity of the Bam earthquake itself as sufficient to explain much of the damage. The seismograph records show that the vertical component of the vibrations near the site of the Arg was greater than the horizontal component, reaching a level of almost 1*g*. With such intense vertical vibration, the loads on the

Figure 1. The Arg-e Bam upper citadel before and after the earthquake. Before photo by James Conlon, 2003.

Figure 2. Evidence of termite damage in a wall of the Arg-e Bam showing extensive deposits of frass with insect tunnels.

earthen walls were rapidly cycled from losing their overburden weight to having to sustain double that weight. Because buildings are designed to carry well more than their own weight, the vertical earthquake forces are not generally considered to be as dangerous as the lateral forces. However, for earthen construction, when the overburden weight on the walls is reduced or eliminated, the lateral forces can be far more destructive than if there were only lateral motion. In addition, with vertical forces of almost 1*g*, the ancient walls were forced to sustain almost double the weight with each cycle. As will be described below, the degraded state of the inner cores of some of these walls may simply have been unable to sustain this momentary additional weight. Even so, the extent of the collapses in the Arg was greater than one would have expected. There was almost no middle ground. Almost every structure suffered partial or total collapse into formless piles of rubble, while, of those parts that did survive; some had very few cracks.

The destruction of earthen and masonry structures in large earthquakes is often accepted by observers as inevitable. Thus, inquiry into the causes of such destruction often stops with the analysis of the lateral forces measured against the capacity of the unreinforced earthen structures without consideration of other factors such as pre-existing pathologies. Yet one important anomaly in the damage distribution in the Arg-e Bam is worthy of further investigation - those structures that had not been recently maintained or restored survived with significantly less damage than did those that had been restored and even strengthened in recent years, see Figures (3), (11), (18), and (27).

Despite its history as a fortified site, all of the walls and buildings in the Arg were composed of unfired earth, and thus were weak and brittle. Yet even if one recognizes this fact, the extent of the destruction was

Figure 3. Unrestored ancient earthen structures including the Shahrbast Wall in the distance after the earthquake. These structures were only lightly damaged.

nevertheless remarkable. There have been few past earthquakes to prepare one for the extent of the destruction seen both in the Arg and in the modern town adjacent to it. There was hardly a single building type, ancient or modern, that did not suffer total destruction. Even many of the steel frame buildings constructed over the last decade ended up with their steel frames wrapped into shapes like pretzels on top of heaps of crumpled infill masonry walls and floors. In the case of the ancient Arg, little remained that resembled complete buildings. A sea of formless rubble extended out as far as the eye could see (Figure (4) and (13)). Even the Governor's House and Tower astride the hill that formed the central symbolic image for the site disappeared, leaving behind ruins that resembled a natural rock outcropping, untouched by human hands, see Figures (1) and Figure (29) for location of sites.

What occurred to cause all of this? Is it explained by the intensity of the shaking alone? In a comprehensive ten-year research project on the seismic behavior and protection of historic adobe building by the Getty Conservation Institute, the researchers concluded that "It is often assumed that an unreinforced masonry structure (such as adobe or brick) is safe only while it is largely undamaged, that is, if it has not sustained substantial cracking. The usual analysis assumes that once cracks have developed the materials have lost strength and continuity - and therefore the building is unsafe. However, a thick-walled adobe building is not unstable after cracks have fully developed, and the building still retains considerable stability characteristics even in that state" [2].

Figure 4. View of the ruins of the Arg-e Bam.

Since it took only a little over 10 seconds for the earthquake to level much of the Arg-e Bam, the Getty project's important findings on adobe structures clearly cannot be applied to this site. Why did the Arg prove to be so unstable? Shouldn't the structures and homes, with their thick earthen walls, have remained standing, even if heavily cracked? Were they simply overwhelmed by the unusually large surface shaking for a 6.5 earthquake, or is this now an unsettling exception to the Getty Seismic Adobe Project's findings? In either case, does this mean that the rest of Iran's most celebrated monuments, many of which are largely constructed of unfired earth, eventually may suffer the same fate?

2. The Citadel and Walled City of Bam

The Arg-e Bam has been recognized as the world's largest earthen complex. Unlike many earthen monuments that are clad with brick or stone, the structures in the Arg were entirely composed of unfired earthen construction. This construction was of two distinct types - unfired "adobe" masonry, known in Farsi as "Khesht", and built up earth or "cob" construction, known as "chineh" [1], see Figure (5).

Even the arches, vaults and domes were constructed of sun-dried bricks using a technique of construction that avoided the need to provide structural centering. Both types of construction could be found in many of the structures, sometimes in layers where the later work, including 20th century restoration work, would be in Khesht, while the original work would be chineh, see Figures (7) and (17).

The news accounts that spread around the world gave the impression that tens of thousands of people died in ancient mud buildings. Instead, almost all of the 30,000 who died in the earthquake were in

Figure 5. Chineh wall inside the Arg-e Bam that was only slightly damaged in the earthquake.

buildings that were less than thirty years old [4]. For five decades prior to the earthquake, the Arg was an archeological museum. At the time of the earthquake, which occurred at 5:27*am*, only three people were sleeping in the Arg complex. The two guards sleeping in the gatehouse were killed, but the chief conservator, who was sleeping in the archeology office in the Arg, was rescued from under the rubble. Had the earthquake happened during the daytime, there undoubtedly would have been more fatalities in the Arg.

As an archeological site, many of the structures in the Arg were already in ruins prior to the time of the earthquake. The walled town was gradually abandoned in the nineteenth century as people migrated out to houses located in the date palm orchards nearby. Gradually the houses and public buildings in the Arg fell into ruin through a slow process of erosion of the earthen walls and domes. Only the structures on the rock outcropping continued to be used and maintained as a military base until vacated under orders from Reza Shah following the demise of the Qajar Dynasty in 1925, see Figure (6).

Beginning in 1953, the site became recognized as a nationally significant historic site and a gradual process of conservation and restoration began. Most of the restoration work has been carried out over the past 25 years. Some of the ruins in the shadow of the military citadel were restored back into complete buildings. The final step in this restoration process was to plaster the exterior surfaces with a layer of mud plaster reinforced with straw. Most of this modern-day restoration work appears to have been done with square sun-dried bricks, rather than in chineh.

Figure 6. Late Qajar Period (19th Century) view showing soldiers in the inner citadel.

Figure 7. View of collapsed outer walls of a round tower. The Khesht construction of the outer layer has fallen off of the earlier inner layers that are most likely a combination of periods of building in different methods.

3. Damage to the Arg-e Bam

The following observations on the damage to the Arg were made over a brief two-day series of visits to the Arg, during a seven-day period in April 2004 when the *UNESCO-ICOMOS-ICHO* Workshop was held. The following explanations of the causes of the damage are hypotheses based on this rapid survey. Definitive determinations on all of the causes of the damage could not be done during such a short visit, but it is hoped that these observations can help to define areas for further research.

At first view, the damage to the Arg is so extensive as to defy any attempt to classify or interpret it. The structures were pulverized, often leaving only mounds of rubble at the base of a few remaining standing walls and piers. Few of the walls survived to their pre-earthquake height, and many of those structures that had been fully restored back into buildings were returned to a ruined state with less remaining standing than had existed prior to the last fifty years of restoration work.

After an exploration of the site, some patterns in the damage began to emerge. These included the following: (1) the circular structures, such as the turrets on the ramparts, fared worse than the long straight walls and rectangular structures (Figure (1)); (2) the Governor's House and other structures on the top of the hill were more completely destroyed than were the structures lower down the hill (Figure (1)); (3) almost every structure in the Arg that remained standing showed evidence of the onset of damage through the spreading to their walls from the inside-out as evidenced by the preponderance of vertical cracks, see Figures (7), (8), (16) and (17); (4) most of the earthen masonry domes and vaults in the complex, many of which had been rebuilt in the late 20th century, collapsed. The largest dome in the complex on the icehouse, a structure that was outside of the walled town that had been converted to an auditorium, collapsed as if punched in.

With regard to interesting examples of surviving structures, one could not help but notice the following: (5) a brick reconstruction of a structure with internal vaults over an ancient water cistern in the center of the stables courtyard, see Figures (9) and (10), survived with no evidence of even so much as a crack from the earthquake. In aerial photographs taken in 1974, the cistern was uncovered and the current structure is a recent reconstruction in modern fired brick masonry. (6) The outer ramparts on the south, east and west sides of the walled city suffered a great deal of damage, with the loss of their projecting turrets and complete destruction of the top crenellations and walkway, yet the north facing ramparts survived in better condition, see Figure (18). (7) In the structure known as the "Small Caravansary", the second level of the side that had a series of buttresses along the outside wall collapsed, whereas the opposite side, which had no buttresses, survived almost intact, see Figure (19).

Most intriguing and significant, perhaps, are (8), those structures that had been maintained and

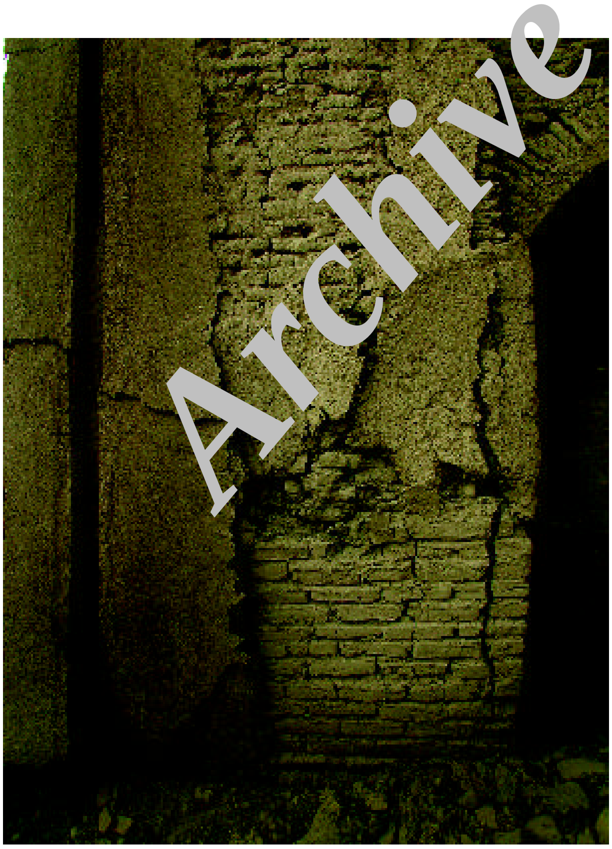

Figure 8. Pier in a partially collapsed section of the Caravansary showing the bursting of the outer layers from internal expansion from the earthquake vibrations.

Figures 9 and 10. Before (November 2003) and After (April 2004) of the same view of the Stables courtyard showing the superstructure over the cistern that was recently reconstructed in fired bricks (Before photo by James Conlon, 2003).

repeatedly modified and expanded over time (such as the structures of the inner citadel) and those structures that had been partially or wholly strengthened and restored during the late 20th century (such as the outer ramparts and buildings of the lower town) fared significantly worse than did those ancient structures - both inside and outside of the Arg - that had not been maintained, modified or restored.

The unmodified and restored structures included most of those in the north-west section of the walled town known as the "Konari" neighborhood, and also those structures just outside of the Arg to the north-east including the tall "Shahrbast Wall", (Figures (3) and (20)) located near the icehouse, and the "Khale Dokhtar", (Figure (28)) located on the opposite riverbank to the north. Some of these surviving unrestored structures are of considerable size and height, and were undoubtedly subjected to shaking of close to the same characteristics as the rest of the Arg, but they remained standing, except for some smaller parts that broke off (Even in these few collapsed sections in the Khale Dokhtar and other structures, termites were also in evidence), see Figures (3), (11), (20) and (27).

Figure 11. Unrestored ruins in the Konari neighborhood of the Arg-e Bam that survived the earthquake with comparatively little damage.

The question that presented itself after these observations was: Is there any single condition that can explain all of these phenomena? During the brief study of the site, two unrelated experiences have contributed to my assessment of what may have caused so much damage, in addition to the high frequency vertical earthquake vibrations. One was the discovery of the termite infestations on my first visit to the Arg, and the second was the chance experience of the largest aftershock to be felt at the site in many weeks. The aftershock, 3.8 on the Richter Scale [5], rolled through the site at 7:10 *am* on the 20th of April. Fortunately that was a day that a small group of us had visited the site shortly after dawn. Standing in the middle of the Arg, the aftershock was felt as a high frequency vertical vibration. It can be described as being like standing on a platform above an engine that was just starting up, but not firing on all cylinders. It lasted only for about four or five seconds. A small amount of dust rose from the complex, but no further damage was sustained.

This vibration was at the opposite end of the spectrum from the kind of earthquake that had, for example, affected Mexico City in 1985 or even San Francisco in 1989. Emanating from directly below the site, rather than from some distance away, the waves caused vertical shaking and vibrated at a high frequency. The earthquake records from the one instrument that was in Bam that was located near the site of the Arg recorded strong vertical vibrations of between 15 and 20*hz* (cycles per second), a higher frequency than the predominant horizontal vibrations that were about 10*hz* [6]. Strong high-frequency vertical shaking alone is capable of causing extensive damage to load-bearing earthen and masonry structures, but there had to be a plausible explanation for the counter-intuitive observation that the unrestored parts of the complex did better than those that had been strengthened and restored. That is where the issue of the termites enters into the picture.

I first noticed the insect damage on the one rampart wall in the center of the complex that survived the earthquake intact, the "second wall of the Governmental Quarter". There was one small area on this wall that had been broken open, exposing the inner core of the wall. Insect tunnels were visible on this newly exposed section, and the entire surface was covered with frass (fecal pellets).

I followed this observation with a crude visual experiment. During the walk out of the Arg, selecting walls at random, I looked to see if similar insect evidence could be found on other broken surfaces. In every instance, insect damage was in evidence on each of the newly exposed inner surfaces that had been broken open by the earthquake. This evidence consisted of both tunnels into the still standing portion of the walls, and large amounts of frass on the interface between the fallen and standing portions. The earth itself in these areas was extremely friable.

There was evidence that the surfaces between many of the fallen and standing portions of walls had been the interface between earlier and later work. This interface had contained many channels left by the insects that gave access to those tunnels that drove deeper into the (usually) older material that was still standing.

Termites live in earth and feed on organic material - that is, the same kind of cellulose that is frequently used to reinforce adobe bricks and the earth stucco used in earthen construction. Thus, the concentration of termite passageways in the interface between newer and older construction appeared to have weakened and separated the different layers of construction.

Figure 12. View of section of earthquake-caused collapse showing timber consumed by termites.

If further research does prove that the termites were concentrated in the interface between zones of construction of different periods, it can explain why the later construction tended to fall off of the older cores of the walls. In addition, once they have perforated the matrix of the earthen wall, the termite tunnels may have contributed to the further drying out of the earth itself, with a commensurate loss of cohesion that comes from an excessive drying out of the earthen structure [7].

4. Collapse from the Inside Out

The termites are only a part of the larger problem of the internal degradation of the walls, but seeing how pervasive the insect tunnels were throughout the ruins did alert me to consider the possibility that the many of the collapses in the Arg may have initiated from failures deep inside the thick walls.

As I explored the ruins of the still impressive earthen complex, it was, of course, difficult to come up with a single theory that could explain the nature and extent of the damage. I had expected to experience the kind of damage described by the Getty Seismic Adobe Project with the classic signatures of structural weaknesses inscribed on them: shear “X” cracks, cracks propagating out from the tops of windows and doors, collapsed corners, overturned walls, etc. However, in the Arg, even the usually common diagonal or "X" cracks were relatively rare. It appeared as if the structures had exploded from the inside and crumbled straight to the ground in a scatter of small pieces. Rubble was everywhere. It formed a mat of broken material that in some places was almost as high as the still-standing remains of the walls. The previously completely restored Grand Mosque, for example, was completely unrecognizable after the earthquake. In the rubble pile, there was even barely enough left intact to discern the outline of what had been its large courtyard, see Figure (13).

Figure 13. Ruins of the Grand Mosque. The north-west section of the main courtyard was on the right side of the view.

It was only after having a chance to take in all of the evidence that could be seen in four short visits to the site over a six-day period that a pattern began to emerge. First it became apparent that walls did not crack into a series of larger sections that could rock back and forth as the Getty project had predicted based on the adobe buildings they had studied.

Instead, the Arg buildings appeared to have responded to the high-frequency vibrations like unconsolidated earth fill. The study of the situation thus seemed to require a change of discipline - from structural engineering to soil dynamics.

The more we examined the site, the more compelling this explanation became. In a number of locations there was evidence of lateral spreading of the kind that one would expect to find around the shore of a lake - but in this case it was located on dry ground where historically the surface had been built up to create the level terraces on which the buildings were constructed on the lower hillside. One section of the terrace that supported a building above the stables collapsed altogether, carrying away the front half of the rooms constructed on it, see Figure (14). The round turrets appeared to have failed at the bottom, instead of splitting apart at the top as one might have expected. Their seemingly strong walls were simply pushed out at the base, with sections of the upper walls having slid down the rubble with the upper ornamentation remaining as the only recognizable pieces left.

Figure 14. Buildings above the Stables Courtyard that collapsed from the lateral spreading failure of the retaining wall and fill beneath.

While trying to make sense out of this chaos, I recalled (without remembering the name of the site) a pair of lecture slides seen years before of a truncated stone pyramid in Central America that had an earthen core. The first image was of a seemingly indestructible squat stone pyramid. In the second image, taken after an earthquake, the stone exterior of the structure lay scattered on the ground, leaving only a lower mound of earth where the structure had been. The earthquake had simply blown the heavy stone shell apart with explosive force as the earthen core shook down to a new level [8]. It seemed an implausible kind of damage at the time, but, after seeing the same phenomenon in the Arg, the parallel was unmistakable. If the earthen core in a wall loses its cohesion, then the settling of the core can blow out of the containing exterior surfaces. It is like a child's sand castle on the beach when stepped on by an older brother.

The aftershock at 7:10*am* on the 20th of April provided a palpable sense of what had happened during the main shock. As the records did show, the main earthquake on December 26th was recorded as having a high frequency vibration, particularly in the vertical direction. From the sensation felt during the aftershock, it did feel like the kind of vibration that could cause soil subsidence - much the same way that a vibrator causes freshly-placed wet concrete to flow. The experience here began to explain each of the seemingly disparate and sometimes counter-intuitive phenomena described in the list above.

For example in the case of (1) the first observation, the particular vulnerability of the circular turrets may be explained by the fact that they had contained large amounts of unconsolidated fill in their bases. One of the few that survived is to the right of the 2nd gate (Figure (15)), and it has a timber floor diaphragm with timbers penetrating the walls located beneath the upper windows, with a room, rather than solid fill, below. The absence of the fill, combined with the effectiveness of the floor diaphragm may have been instrumental in holding it together.

Figure 15. One of the few surviving turrets has a room in its base, as shown by the ground floor window. The floor diaphragm timbers extend through the walls, and are now visible after the stucco fell off. The collapsed masonry and stucco is from what appears to be a modern-day modification of the shape of the tower in the tradition of Viollet-le-Duc. The tower's original surface underneath is intact.

In the case of (2) the collapse of the structures at the top of the hill (Figure (1)), this seemed to be caused in part because the failure of the retaining walls and fill that had been constructed up from the lower hillside to widen the platform at the top of what had originally been a narrow rock outcropping. The failure of (3) the walls of many of the buildings and ramparts was also consistent with the lateral spreading of the material in the cores of their walls, with the exterior adobe bricks being forced out as manifested by the greater frequency of vertical cracks as compared to diagonal cracks, see Figure (16) and (17).

Figure 16. Collapsed round turret on the ramparts that shows evidence of having burst apart from collapse of internal layers.

Figure 17. A massive pier composed of different periods and types of Khesht and chineh construction that have separated from each other during the earthquake.

In the case of (4), the collapse of the domes throughout the complex, many simply may have followed their bursting supporting walls to the ground. Others which collapsed inward, like that of the Icehouse, suffered from the effect of the intense vertical vibrations on the soft adobe brick masonry. The momentary doubling of the weight of the domed structures was probably more than they could handle. In the case of the Icehouse, the 1974 aerial photographs provide evidence that the part of the dome that did collapse had been reconstructed after that date, as it was missing in those photographs [9].

By contrast to the bursting walls (5), the masonry structure over the cistern in the center of the stables courtyard performed much better despite being of unreinforced masonry. Most likely in this case, the walls were of a uniformly solid and bonded masonry construction without a rubble core. The fact that it was constructed of fired brick would have contributed to its strength, but what may even have been more important was the fact that the walls were of a fairly cohesive material of uniform density without voids or vertical gaps.

As for the better behavior of the north-facing ramparts compared to the other city walls (6), the subsurface soil conditions along the riverbank where the wall is located may account for some of this difference because the alluvial soils may have served to damp out some of the vibrations, rather than intensify them, as is often the case with earthquakes where the epicenter is farther away. Further research is needed to determine whether this may be one explanation. Also, like the nearby Konari neighborhood, these walls had not been altered and restored along their tops as much as had the other walls around the Arg. It was the newer restored upper level battlements, walkways and crenellations that consistently suffered the most, possibly because of the different densities and vibration response of the new and old material and the additional weight.

Figure 18. North-facing ramparts that were significantly less damaged in the earthquake than the other city walls. Notice that the crenellations are still intact on this one section, the only section where that was observed to be the case.

The second-to-last item (7) is the Caravansary, where the rooms on the second level of the buttressed west side of the complex collapsed, leaving the east side that lacked buttresses largely intact. The buttresses themselves were also damaged, with one collapsing from the crushing of its base.

The story of this complex became even more interesting when I learned from the old photos that the side that collapsed had been almost completely reconstructed only a few years earlier, whereas the still standing side had mostly survived from antiquity. In aerial photographs of the caravansary taken in 1974 [10], the domes on the east side were almost completely intact, whereas on the west side they had collapsed. At that time, the buttresses on the west side only extended up to the level of the first floor. As late as 1996 the condition of both sides was similar to 1974, except that the small holes in the east side domes had been fully repaired [11].

Figure 20. The interior of the unrestored "Shahrbast Wall" showing 3-story high walls that survived the earthquake. Notice the older section with later work constructed around it. This is a good example of the onset of damage at the interface of construction of different age and type, as a small area of collapse has revealed this interface. Notice the debris on the ground.

Figure 19. The ruins of the Caravansary show that the domed rooms on the second level behind the buttresses have collapsed, while the ones opposite still remain. There are no buttresses behind the external wall of the opposite side. The base of the 5th buttress is crushed.

At the time of the earthquake, photographs show that the restoration of the west side of the Caravansary had been completed [12]. The domes had been reconstructed and the west wall and buttresses had been extended up to the roof level. Ironically, in the earthquake it was this newly constructed and fully buttressed side that fell. This was simply one more example of the finding that the areas with the greatest amount of strengthening, reconstruction, or even of continued maintenance were the most heavily damaged.

All of this evidence taken together seems to point to a phenomenon where those earthen walls that are composed of material of different densities and construction characteristics resulting from their different phases of construction, repair and reconstruction, proved to be more vulnerable to the earthquake vibrations. As long as one perceives of the earthen construction as having a uniform composition, it is difficult to understand why the strengthened and restored walls would fare worse than the unrestored and naturally eroded walls. However, the succeeding phases of construction in the Arg over the centuries had produced walls of a very different composition than that of a newly constructed earthen building.

No longer did many of these walls consist of horizontal layers of earth or sun-dried bricks, and those that did consistently appeared to be less damaged. Instead, through generations of erosion, repair and remodeling, many of the walls had evolved into a series of vertical layers of earth, standing together like books on a shelf without bookends. Each of the different layers was of a different density and cohesion resulting from the different ages, construction characteristics, and degradation. For example, modern Khesht (adobe masonry) frequently encased older chineh (cob) construction (Figure (17)), and the organic material used for reinforcement had rotted or been consumed by insects, leaving cavities and friable earth (Figure (12)).

Further research is needed on this subject, but it was only after I began to interpret what I saw at the site as the behavior of vertically disconnected unconsolidated earth, rather than as the uniform horizontally bedded earthen construction of the sort analyzed for the Getty project, that a possible explanation for the nature and extent of the earthquake damage began to emerge. Based on the Getty research, the thick walls of the ramparts and main citadel in the Arg of Khesht or chineh construction would normally be expected to be the most resistant, rather than the most vulnerable as they turned out to be. If the hidden interior parts of the walls are composed of a series of vertical segments, and especially if the inner segments had large voids, crevices, and dried-out unconsolidated fill that lacked connections to the outer layers, the high frequency vibrations of this earthquake could cause the inner older and more degraded portions of the walls to settle. This then could exert a horizontal force from the inside-out onto the outer layers at the base of the structures, causing the walls to collapse, not by tipping over, but by crumbling in place.

In addition, variations in the density and cohesion in the earthen layers in a wall, particularly resulting from different periods of erosion and reconstruction and changes from chineh to Khesht quite possibly can cause the earthquake vibrations - particularly vibration in the high frequency range experienced in Bam - to ricochet off of the layers of different densities, causing the onset of damage from the local intensification of the vibrations. Evidence of such behavior can be seen in (Figure (20)) where the wall began to break out at the interface between two vintages of Khesht construction both of which appear to be pre-20th century. This is a subject in need of further research specific to earthen construction in order to establish if this phenomenon can be explained in this way, but such research may have a significant bearing on the protection of other earthen monuments that have been altered over the centuries. The North and South American adobe structures that were the primary subjects for the Getty research are less likely to be subject to this phenomenon because they are usually composed of uniform layers of adobe masonry.

This is why the observation of the widespread infestation by termites may turn out to be important. Not only did it appear that the ancient construction in the Arg was perforated by the insects, but that the insects had also succeeded in separating the different vertical segments from each other and reducing the cohesion of the inner core of the walls. In a trip to Isfahan after the mission to Bam, during meetings with the professional restorers of several of the historic monuments in that splendid city (Figure (21)), I learned that termites were also found in the walls during the recent restorations. These professional conservators explained that the damage caused by the termites had to be addressed in the restorations by consolidating the earthen cores of some of the walls.

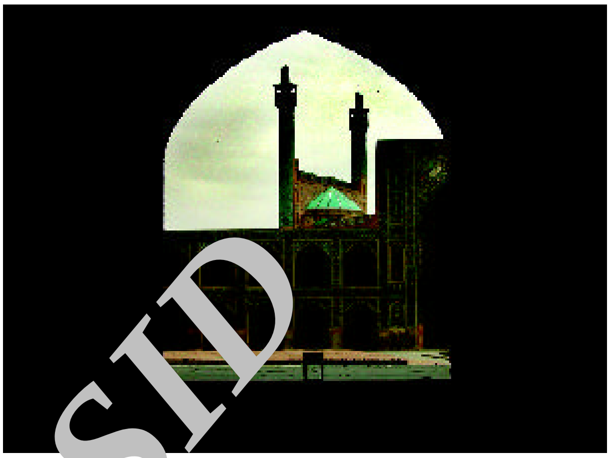

Figure 21. The Imam Mosque in Isfahan, April, 2004. The inner cores of many of these walls and the walls of other great monuments in Isfahan are constructed of unfired clay.

In contrast to this strengthening work in Isfahan, some of the 20th century restoration work seen in Bam may have aggravated the problem. Clay stucco added before the earthquake was reinforced with copious amounts of straw - a material that appeared in many areas to have been consumed by termites. By contrast, the older reinforcement of shredded date palm tree bark appeared to have been more resistant. Perhaps the termite population inadvertently has been increased in modern times, simply because of this "banquet" of non-resistant straw-reinforced stucco.

5. The Risk to Earthen Mounments

What many people do not realize is that new buildings in any country constructed of modern materials to code are not designed to withstand major earthquakes without damage. For earthen structures, elastic analysis procedures provide little guidance on how such buildings will behave in the post-elastic range. Quoting again from the Getty Seismic Adobe Project report: "The sole use of an elastic approach can be justified only when there is a known relationship between the level at which yielding first occurs and the level at which the structure collapses. In the case of thick-walled adobe construction, there is no clear relationship between these two events. … While a strength-based analysis can accurately predict when cracks will occur, it cannot provide insight into the post-elastic performance of adobe buildings".

This report makes a very important distinction between what is described as a "strength-based" approach and a "stability-based" approach to seismic upgrading. The report identifies that the current "conventional engineering approach to seismic retrofitting" is a strength-based approach, which is based on increasing the elastic strength of a building's structural system. They go on to explain that for adobe buildings, a "stability-based approach" is more suitable. The objective in stability-based design is to ensure that the structure remains standing long after the elastic range of its structural system has been exceeded. Since the elastic capacity of adobe masonry is low, seismic hazard mitigation of adobe structures depends on maintaining its stability long after it begins to crack.

The Getty Report then goes on to describe the potential that adobe buildings have for "structural ductility" even though they lack "material ductility". The structural ductility can come from the inherent stability that even the cracked adobe walls can have so long as the cracked wall sections remain bearing one on another. This is an important finding that can be used as effective basis for design for many adobe structures that otherwise would be condemned. However, in retrospect, what the Bam earthquake has proved is that, in spite of the thickness of the ancient earthen walls in the Arg, stability was quickly lost after the elastic range was exceeded. The earthquake on 26th December 2003 was recorded to have lasted only 12 seconds, so the collapse of the Arg was almost instantaneous. Structural ductility thus was not to be found in the structures of the Arg.

Who could have ever known there was such a risk? The interiors of the walls with their voids and degraded materials were hidden. An engineer doing a structural analysis would normally have based the analysis on measurements of the thick walls without anticipating the effect of the fractured and weakened conditions of their internal cores. Research is now needed to find ways to be able to evaluate such walls as non-destructively as possible, and then to find ways to address the kinds of problems that may be discovered that would lead to their rapid loss of structural cohesion when subjected to earthquake vibrations.

6. Why did the Arg-e Bam Prove to be so Vulnerable?

If the changes to the walls of the Arg over the centuries, and during recent restorations can be proven to be a major part of the cause of its wide-spread collapse, then there are two remaining questions that need to be asked. The first is:, Since the Arg is located in a known earthquake region, why was its construction not more responsive to the threat? Before answering this question, one must ask whether or not the original construction prior to its alteration and degradation over time was in fact designed to be more resistant. These are both particularly difficult questions because the subject of the inquiry is archaic construction using a limited palate of materials - namely unfired earth with a small number of undressed timber logs - not something that provides much opportunity for modification to resist large earthquake forces.

Earthquake resistance is not an absolute. One must alter one's expectations to reflect what could be achieved in a culture where only unfired earth and a limited amount of timber were available. In the present, expectations of earthquake safety have been shaped by the existence of steel, either as the structural building material itself, or imbedded into concrete, or even when used to reinforce the connections between timbers. The frequent catastrophic failures of modern buildings of steel and concrete, as we have seen in Bam, in the case of steel, and other recent earthquakes in the case of reinforced concrete, notwithstanding, the existence of steel as a building material has raised expectations, making it harder now to recognize pre-modern mitigation efforts.

Traditional construction - particularly in a desert environment - did not have the luxury of an abundance of timber, much less access to modern steel. Much of what could be done was the product of trial and error leading to the evolution of building practices over many centuries. Thus, out of all of the influences on the evolution of construction practices, it is not easy to discern those specifically that are a response to earthquakes. Earthquakes themselves are not always the same. The December 26, 2003 earthquake in Bam was only 6.5, but it was a shallow earthquake with its epicenter located almost directly beneath the Arg-e Bam. The likelihood of being directly above the epicenter of an earthquake is significantly less than being nearby. Thus, it is entirely possible that the Arg had never been subjected to such a high frequency vertical vibration over the prior 2000 years of its history [14].

The earthquake risk most often analyzed by computing the static equivalent forces on structures, but in this case, the frequency of the vibrations may have been particularly significant. Even a small difference in the location of the epicenter, would have shifted the ground shaking under the Arg away from such high frequency vertical vibrations to a lower frequency vibration with a smaller vertical component. How this may have affected the spectrum of damage in the Arg is difficult to determine, but important to know because it can shed light on the degree to which other monuments are at risk. If high frequency is a large part of the cause of the damage, the odds of a recurrence under other monuments is less than if a broad range of frequencies will cause similar damage.

7. An Approach to Mitigation Based on Historical Precedent

In order to recognize pre-modern seismic mitigation practices, one must accept that people would have responded to earthquakes in the past, just as they do today, with consideration of what could be done to reduce the risks. Whether they were successful or not does not change the fact that in centuries past, people did not always simply acquiesce to the risk. In Italy, Turkey, and some other seismically active areas, where earthquakes have been relatively frequent, such that there is living memory from one generation to the next, there has developed what some scholars have defined as a "seismic culture" [15].

For example, there are many types of stone construction around the world, but some forms, such as rubble stone, have proved to be less resistant than dressed and horizontally bedded ashlar, yet in many places rubble stone is all that is available or affordable. In parts of Turkey, and in Kashmir, both brick and rubble stone construction were often modified by the laying of timbers into the wall much as if one had laid a wooden ladder horizontally onto the partially completed wall beneath and above the windows and at the floor levels as masonry construction proceeded. The timbers were placed in the wall not to provide a frame, but to resist the propagation of cracks and the lateral spreading of the masonry [16]. In Kashmir, the timber-laced masonry was often rubble made up with small stones or bricks set into a thick bed of clay mortar with the timbers holding the walls together. In Srinagar, after an earthquake in 1885, a British visitor observed:

> *Part of the Palace and some other massive old buildings collapsed ... [but] it was remarkable how few houses fell.... The general construction in the city of Srinagar is suitable for an earthquake country; wood is freely used, and well jointed; clay is employed instead of mortar, and gives a somewhat elastic bonding to the bricks… the whole house, even if three or four stories high, sways together, whereas more heavy rigid buildings would split and fall* [17].

There are few people today who would consider using "clay… instead of [lime] mortar". For years, the accepted wisdom is that not even lime mortar is strong enough. It must now be cement. Many national building codes often reflect this. More significantly, this 19th century quote highlights the virtues of flexibility over strength.

Ensuring stability in earthquakes of earthen structures like those in Bam is clearly more difficult without the timber that was available in Turkey, Kashmir and other regions. The more lush sections of Northern Iran are reported to share the timber-laced building tradition found in Turkey, but in dry deserts of southern Iran people do not have the luxury of using extensive amounts of timber, but the date palms logs were sometimes imbedded into the walls as well as used to support floors (Figure (22)).

Figure 22. Collapsed section of the main gateway showing imbedded timber reinforcement of the Khesht wall.

To begin to understand what may have been done in the past with earthen construction in response to earthquakes it is helpful to begin by looking not only at what fell, but what did not. For this we turn to the chineh garden walls around the date palm orchards throughout the city. The chineh garden walls are generally about two to two-and-a-half meters high and 50-100*cm* thick at the base with a batter reducing them to only a few cm thick at the top. Most of the date palm groves in Bam and in Barakat are surrounded by walls of this type. The Iranian chineh construction found in Bam is characterized by a series of bands of clay that are about 50*cm* high that represent each "lift" in the construction process. These lifts were constructed along the wall from one end to the other, and then made smooth and level on the top before proceeding with the next lift, see Figures (3), (5), (23) and (24).

Figure 23. Chineh garden wall, probably of recent origin, in Baravat (near to Bam). This wall shows the cracks that commonly exist in chineh walls, and how the layered construction helps to ensure stability by allowing the cracked sections of the mud layers to perform like large blocks of masonry.

Figure 24. South-facing outside wall of the stables courtyard showing how the layering of the chineh walls has interrupted the cracking and collapse of sections of the wall, thus helping to maintain the stability of the partly undermined upper part of the wall.

This differs from Northern European cob construction, which lacked such clearly defined horizontal interfaces between the lifts. There may have been a number of reasons for this construction detail in chineh, such as water shedding, but one structural reason for it may have been that it served to stop the continuous propagation of vertical cracks through the wall, a problem that is all the more acute in a dry climate. Because they are constructed only of uncompressed dried mud, they began their life with many vertical cracks and checks from the initial drying out process. In fact, the Getty Seismic Adobe Project report states: "Substantial cracks nearly always exist in historic adobe buildings as a result of past earthquake activity, wall slumping, or foundation settlement. Cracked walls are a typical feature of these buildings" [18].

Throughout history, Iranian builders would have striven to avoid the negative structural effects of this inevitable cracking as much as possible. This would have been done for stability in general, not just because of earthquake risk but the earthquake risk may have contributed to the evolution of the system that was used, while the local limitation on resources would have limited the builders to the use of unfired earth. The horizontal control joints in the chineh walls thus may be a result of this effort to control the effects of crack propagation by interrupting the progression of cracks through what would otherwise have been a uniform material.

Many chineh walls, both ancient and modern, did prove to be remarkably durable in the 2003 earthquake. As one approaches the Arg, passing through areas of gradually increasing damage, these walls are seen to have remained standing even when nearby houses and multi-story steel frame buildings were collapsed. Near the Arg, the damage to the garden walls is clearly greater, but large sections of them have nonetheless remained standing that were both parallel and perpendicular to the direction of the earthquake waves. Also, many of the walls of the unmaintained and unrestored structures mentioned above that survived the earthquake largely intact were of chineh construction, see Figures (3), (5), (11), (18), (20), (24), and (27). Both those walls, and the ancient walls of Khesht construction survived intact, with a few minor exceptions, whereas, as mentioned above, it was those walls in the Arg where chineh was later reinforced with Khesht that the damage was observed to be the greatest, see Figures (7), (16) and (17).

When examining the historic evolution of the chineh with its control joints, it may be relevant to also turn to the construction practices that evolved in ancient Rome. In Rome the surviving archeological remains are filled with walls of a form of natural pozzolanic cement. These great lumps of material have shown a remarkable durability, but one feature in many of these walls stands out. Every meter and a half or so was a horizontal band of fired brick masonry that extended through the walls. The early Roman bricks were essentially a flat thin tile. The original purpose of these bands is not known from any literature source, and archeologists often differ in their interpretations, but it is clear that they did function as "crack stoppers". By interrupting the uniform matrix of the natural cement with the bedded layer of bricks in mortar, the inevitable cracks that occurred in the cement layer were interrupted, giving added stability to the walls, see Figure (25).

Figure 25. Long Wall, Hadrian's Villa near Rome showing the bands of brick that were laid into a wall constructed with natural cement with a tile facing. The crevices are the result of the later chipping out of the bricks for re-use.

In the Arg-e Bam, some of the chineh walls had a band of adobe bricks in between the lifts at the base of the wall. In one of the eastern rampart walls, there appears to have been a row of adobe bricks between each of the several lifts. These may have served a similar function as the Roman bricks even though they were not fired bricks. At the *UNESCO-ICOMOS-ICHO* Workshop, one delegate, Archibald Walls from the *UK*, reported that there are other sites in Iran that do have horizontal bands of bricks laid into walls of chineh.

These and other Iranian examples are worth exploring for further information on the effectiveness of such horizontal bands of masonry laid into earthen walls, but the lesson to be learned is that what we sometimes only think of as architectural details originally may have been developed to serve more practical structural needs. This point is reinforced by the following example in Istanbul: during the 1999 Koçaeli earthquake, the only part of the ancient city walls to collapse was a tower that had been completely reconstructed in new masonry only a few years before, see Figure (27).

The next tower, see Figure (26) - despite its heavily decayed and cracked condition - remained standing. The surviving ancient tower had horizontal brick bands that extended through the rubble stone core of the wall. The restorers of the new tower only placed the brick bands on the surface of the wall as a veneer, constructing the tower with thick walls of rubble set

Figure 26. Surviving portion of the original Istanbul city walls. The cracks and broken section pre-dated the 1999 earthquake.

Figure 27. The reconstructed tower that collapsed during the 1999 earthquake. The bands of red brick on the wall were fake veneers, rather than full layers.

Figure 28. The unrestored Khale Dokhtar, a small Arg (or citadel) on the riverbank opposite the Arg-e Bam that survived the earthquake with the collapse of some arches. The high walls of the massive structure otherwise survived intact (Termites and other insects were also in evidence where the collapses occurred.)

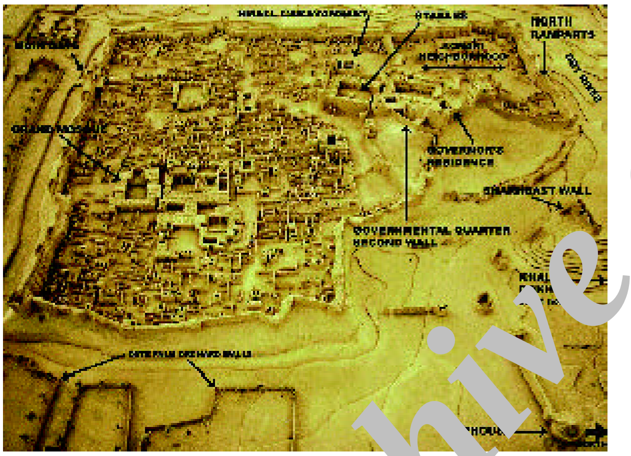

Figure 29. ICHO model of the Arg-e Bam after recent restorations prior to the earthquake.

in mortar clad with cut stone. The lesson that can be learned from this event is that for ancient buildings, structural design and construction practices are part of an integrated system, not separate or unrelated features. The hidden parts of the ancient walls are every bit as important as what can be seen on the surface. Illustrative of this fact, the pre-modern builders most likely understood the importance of the simple concept of crack-stopping since it was one of the few measures that they had at their disposal to improve the stability of the ancient construction in the desert environments.

8. Conclusion

In summary, it appeared to be that the collapse of the Arg-e Bam was largely a result of the internal collapse of the walls resulting from a catastrophic loss of the cohesion of the earth deep within its walls. The initial impression was that the 20th century restoration work itself performed far worse than the ancient work, but it was not always the newer work that failed per se, but the combination of the new and old. In fact, it appeared that the newer work often failed as a result of the internal collapse of the older work on which it was founded.

While it does not explain all that happened, the termite damage is symbolic of the larger issue of the role of time and change in both the science and the art of building conservation. It was only after noticing this infestation that I began to focus on the other aspects of internal wall degradation - the dryness and lack of cohesion of the earthen cores, the decay and consumption of the reinforcing timbers and fiber reinforcements, the existence of small and large voids between vertical layers in the walls, and the evidence that thick earthen walls had burst open before they collapsed. When all of these elements are put together with the particular characteristics of this earthquake with its high frequency vertical vibrations, the collapses of the walls from the inside-out appears to be a plausible explanation for a great part of what happened.

If, after further research, these explanations into the causes of the collapses in the Arg described here are substantiated, it is important then to ask: what are the implications of these findings, not only for the future restoration work in the Arg, but also for the other cultural heritage sites in Iran and throughout the Middle East and North Africa? If, after a 50 year program of restoration, such a seemingly robust earthen monument can be shaken down in 12 seconds, we need to understand why the kind of post-elastic stability described in the Getty research did not occur. Many, of Iran's most splendid monuments are of earthen construction behind their exterior surfaces of carved stone and ornate ceramics. In an earthquake, if the inner layers shift and settle in response to earthquake vibrations, the outward pressure could lead to a blowing out of the walls at their base, causing collapse of the structures. Standard structural retrofit analysis and techniques may neither fully account for this risk, nor mitigate it.

In order to make the best use of the knowledge that can come from an investigation of the damage sustained by the Arg-e Bam, it is important first to understand, as the Getty researchers did, that the destruction of such monumental earthen architecture from shaking of this magnitude should not be taken as a forgone conclusion or as a condemnation of the use of unfired earth as a building material. What the destruction of the Arg does provide, however, is the cautionary message: Buildings are not always as they seem to be when looked at from the outside. This message is particularly profound when it comes to earthen architecture. The transition of the walls of the Arg from horizontally bedded layers to separating vertical segments resulted from centuries of erosion and renewal, but the external look of the walls had changed little over that time. It took an earthquake to open the walls up and reveal that the internal composition of the wall was no longer the same as it had been when originally constructed.

More than any other building material, unfired clay can change over time from cumulative effects of the short repeating cycle of erosion and renewal, and also from a gradual deterioration of the hidden core of the walls, not only from termites, but also from rising damp, water intrusion from the top and sides, differential settlement, gradual compaction, and gradual chemical or mineralogical changes to the matrix of the material. Although of particular importance when dealing with unfired earth, these causes of deterioration can affect many different building materials.

The visual symbol of this earthquake to the world has become the dramatic juxtaposition of the "before" and "after" images of the Arg-e Bam (Figure (1)). However, for the future of both construction with adobe and the conservation of earthen architecture, the symbol should also be the ancient earthen structures around the Arg that did not collapse, see Figure (3), (11), (20) and (28). Without having had modern-day maintenance or restoration, at the time of the earthquake, these structures were closer to the structural form of their original construction dating from centuries past. Having survived the earthquake intact, they stand today as examples of earthen construction that proved to be capable of resisting a major earthquake better even than some of the new steel frame buildings that did collapse. The age of an historic structure thus may be less of a factor than modern-day changes to its fabric, including, ironically, modern efforts to strengthen and restore that ancient fabric.

If this is true, we may need to look no further than some of these modern-day construction and conservation practices to begin to find a solution to the problem. It is at this level that the fate of the Arg becomes intertwined with the fate of the modern town that stood along side. The houses in which people died were modern houses. Their walls may have been of Khesht, but many also had roof beams of steel, and floors or roofs of fired brick. If both the twentieth century restorations in the Arg and the new houses in the town suffered more than the untouched ancient abandoned earthen ruins in the desert nearby, then the problem had less to do with earthen construction per-se than it had to do with the particular form of earthen construction that was practiced in modern Bam. Therefore, both restoration practices and new building construction practices need to change, and some of the guidance for how they should be changed may be found in the heritage of the nation itself, rather than only between the covers of engineering textbooks.

With so many deaths having occurred in buildings with earthen walls, occurring together with the collapse of such a symbolically important monument, these two phenomena have been fused in the eyes of many around the world. Life safety concerns with adobe construction are now tragically highlighted, creating a problem for the conservation of other earthen sites in seismic areas, all of which are now at greater known risk than before the Bam earthquake. By coming to understand the collapse mechanisms in the Arg, one can go beyond the level of blaming a construction material for the poor performance of construction systems. If one stops at the material in the determination of the causes of failures, all discussion stops, and the fundamental need to determine all of the necessary ingredients that constitute earthquake safety will not be achieved.

Although it would seem that it should be easier to design and construct safe structures out of steel and concrete, in practice, this earthquake, as well as other recent earthquakes in Mexico, Turkey, India, Morocco and many other countries, have tragically proved that safety can be elusive, even with modern materials. In many parts of the world, unfired earth is the most available and economical building material. It is also deeply imbedded as part of the history and culture of Iran and the region. While it may be more challenging to construct safe structures using unfired earth, that does not mean that it cannot or should not continue to be done.

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11. Aerial Photograph in The Bam Citadel, a Comprehensive Report, ICHO, (2004). Page 26, Dated 1996 (the same image as used on the Workshop Poster).

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